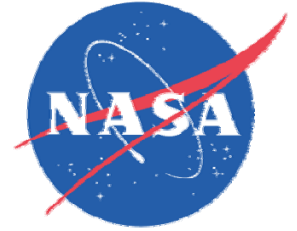


Monitoring Delamination of Thermal Barrier Coatings During Interrupted High-Heat-Flux Laser Testing Using Luminescence Imaging

This presentation showed progress made in extending luminescence-base delamination monitoring to TBCs exposed to high heat fluxes, which is an environment that much better simulates actual turbine engine conditions. This was done by performing upconversion luminescence imaging during interruptions in laser testing, where a high-power CO₂ laser was employed to create the desired heat flux. Upconversion luminescence refers to luminescence where the emission is at a higher energy (shorter wavelength) than the excitation. Since there will be negligible background emission at higher energies than the excitation, this method produces superb contrast. Delamination contrast is produced because both the excitation and emission wavelengths are reflected at delamination cracks so that substantially higher luminescence intensity is observed in regions containing delamination cracks. Erbium was selected as the dopant for luminescence specifically because it exhibits upconversion luminescence. The high power CO₂ 10.6 micron wavelength laser facility at NASA GRC was used to produce the heat flux in combination with forced air backside cooling. Testing was performed at a lower (95 W/cm²) and higher (125 W/cm²) heat flux as well as furnace cycling at 1163C for comparison. The lower heat flux showed the same general behavior as furnace cycling, a gradual, "spotty" increase in luminescence associated with debond progression; however, a significant difference was a pronounced incubation period followed by acceleration delamination progression. These results indicate that extrapolating behavior from furnace cycling measurements will grossly overestimate remaining life under high heat flux conditions. The higher heat flux results were not only accelerated, but much different in character. Extreme bond coat rumpling occurred, and delamination propagation extended over much larger areas before precipitating macroscopic TBC failure. This indicates that under the higher heat flux (and surface & interface temperatures), the TBC was more tolerant of damage. The main conclusions were that high heat flux conditions can not only accelerate TBC debond progression but can also grossly alter the pathway of delamination.



Monitoring Delamination of Thermal Barrier Coatings During Interrupted High-Heat-Flux Laser Testing Using Luminescence Imaging

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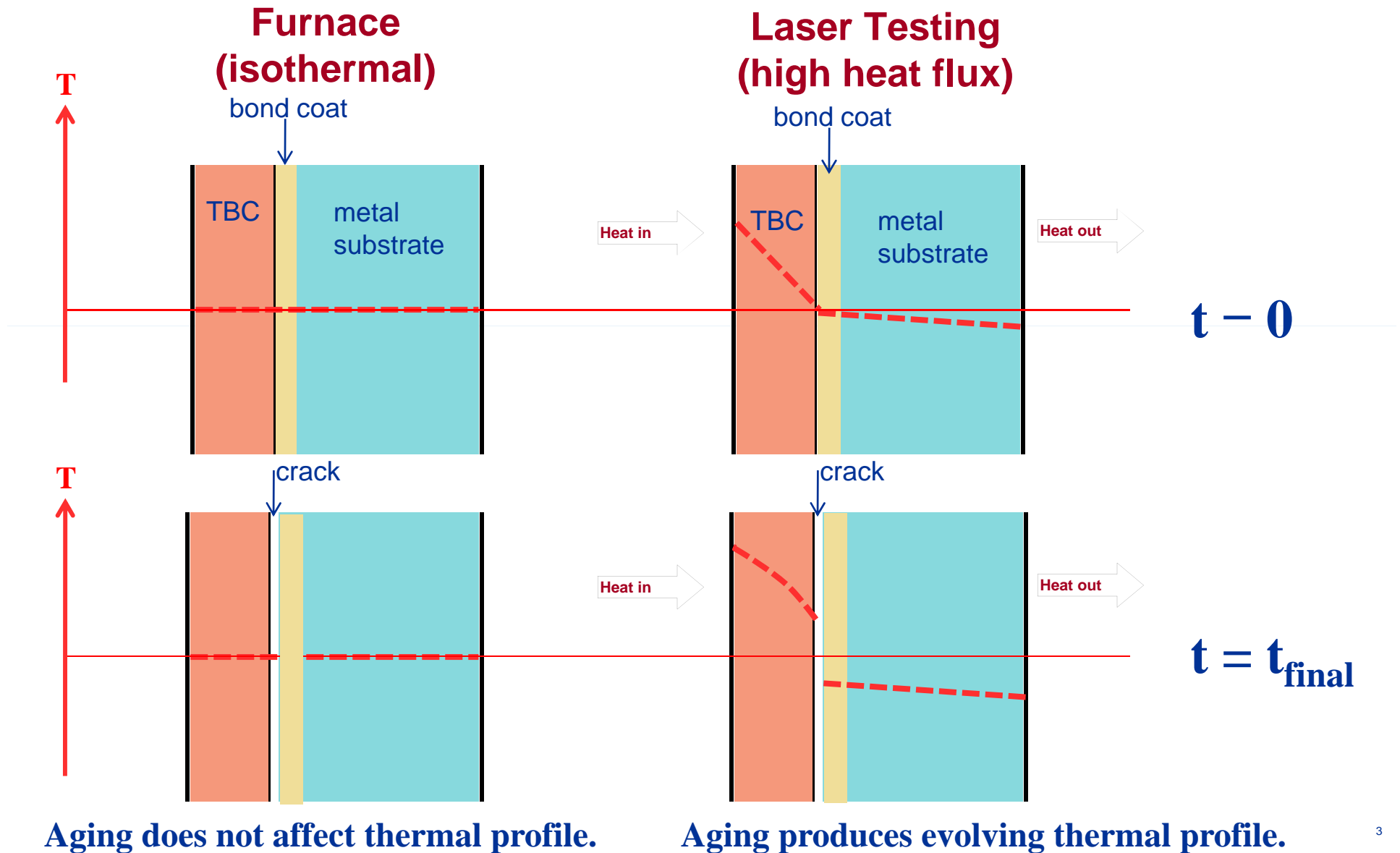
Objective

- Extend luminescence-based delamination monitoring to TBCs subjected to high heat flux.
 - Previous delamination monitoring by upconversion luminescence imaging limited to furnace cycling.
 - Furnace cycling does not adequately simulate engine conditions.
 - Thermal gradients present in high-heat-flux engine environment contribute additional driving forces for TBC delamination and may alter delamination progression pathway.
 - Valid diagnostics for predicting TBC remaining life must be based on measurements of TBCs exposed to engine-like high-heat-flux conditions.

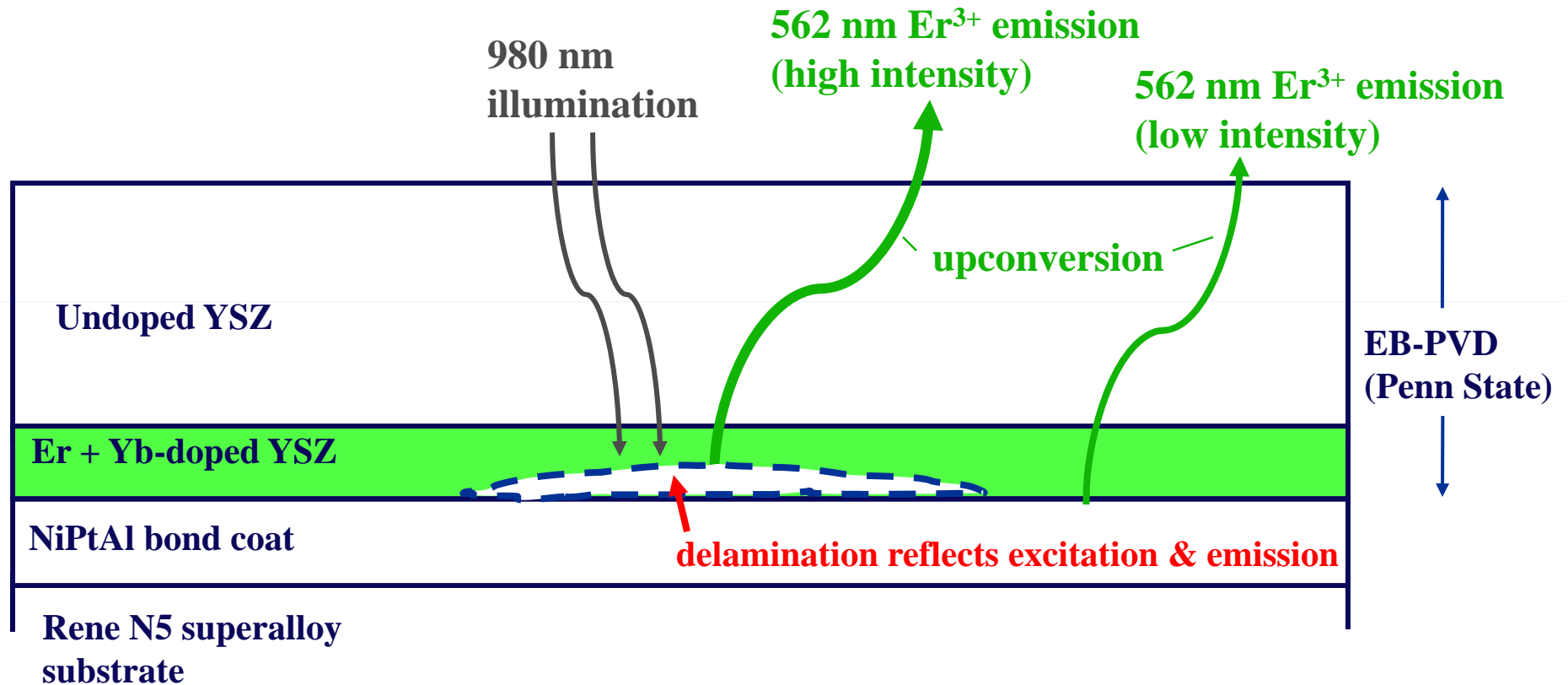
Approach

- Perform upconversion luminescence imaging during interrupted high-heat-flux laser testing.

TBC Temperature Profile Progression Furnace vs. High-Heat-Flux Laser Heating

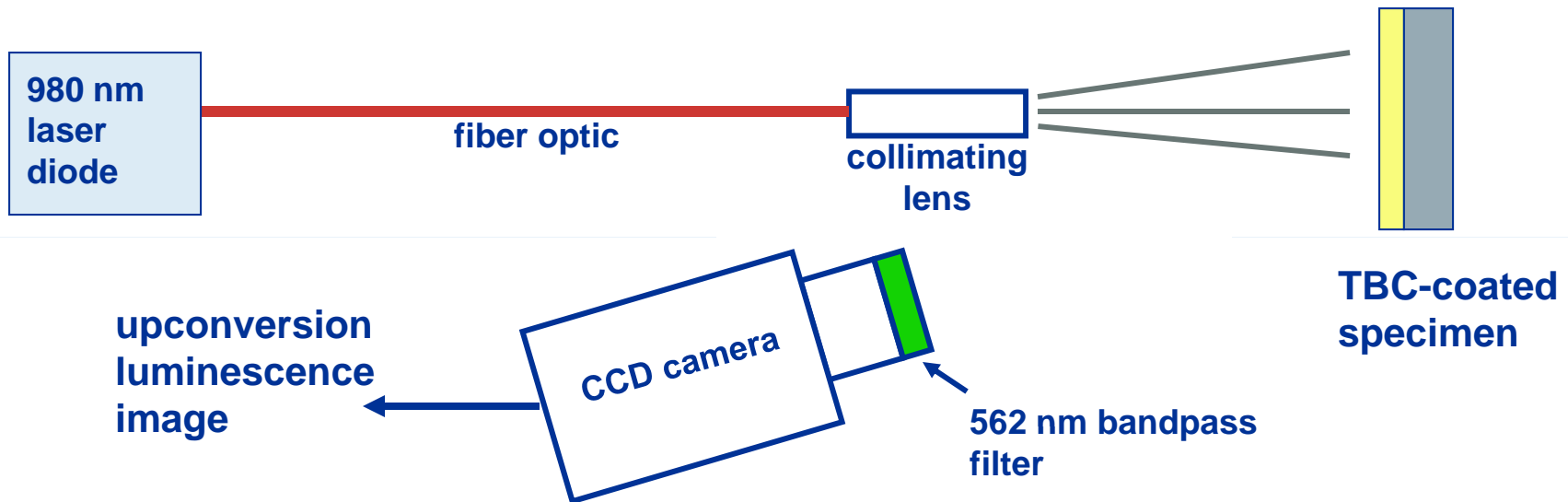


Detecting TBC Delamination by Reflectance-Enhanced Upconversion Luminescence

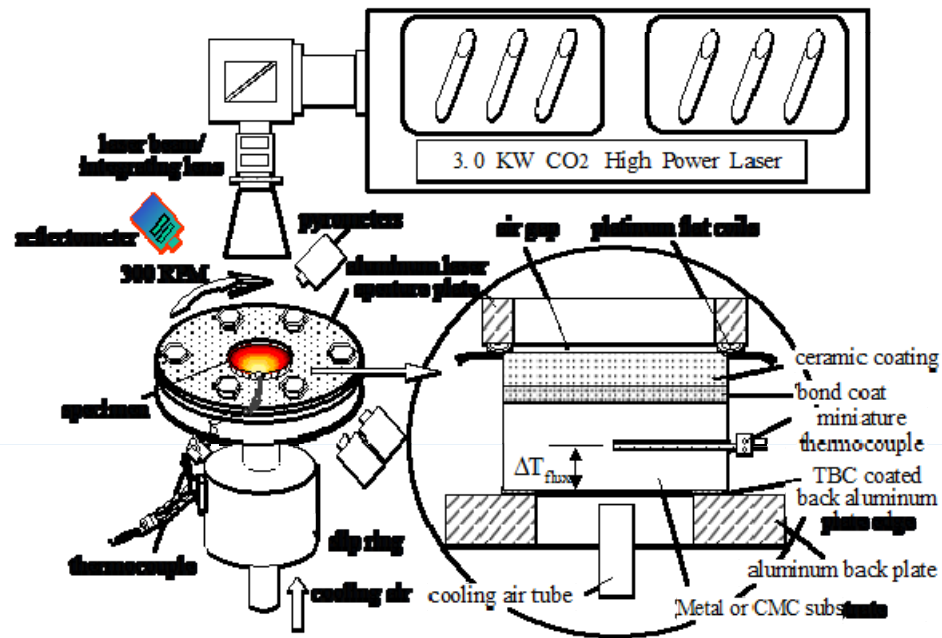


- Two-photon excitation of Er³⁺ produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
- Yb³⁺ absorbs 980 nm excitation and excites luminescence in Er³⁺ by energy transfer.
- Delamination contrast achieved because of increased reflection of excitation & emission at TBC/crack interface.

Upconversion Luminescence Imaging



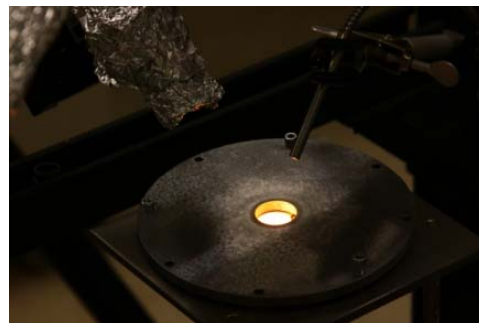
High Heat-Flux Laser Testing



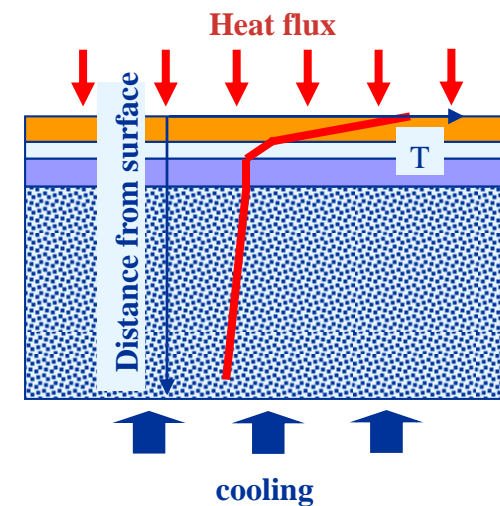
$$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated}$$

$$k_{TBC}(t) = q_{thru} \cdot l_{TBC} / \Delta T_{TBC}(t)$$

•CO₂ laser heating



• High power CO₂ laser high-heat-flux rig



High-Heat-Flux Laser Testing Conditions

Furnace Cycling

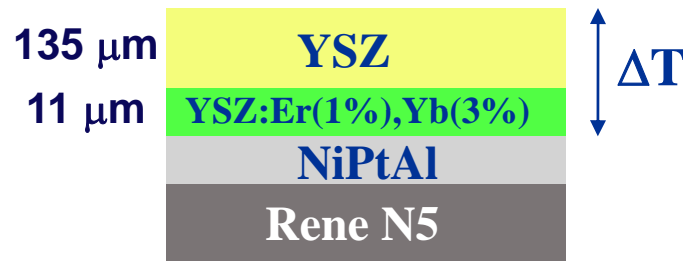
- $q = 0 \text{ W/cm}^2$
- $T_{\text{surface}} \approx 1163^\circ\text{C}$
- $T_{\text{interface}} \approx 1163^\circ\text{C}$
- $\Delta T \approx 0^\circ\text{C}$

Heat Flux Test #1

- $q = 95 \text{ W/cm}^2$
- $T_{\text{surface}} \approx 1290^\circ\text{C}$
- $T_{\text{interface}} \approx 1140^\circ\text{C}$
- $\Delta T \approx 150^\circ\text{C}$

Heat Flux Test #2

- $q = 125 \text{ W/cm}^2$
- $T_{\text{surface}} \approx 1345^\circ\text{C}$
- $T_{\text{interface}} \approx 1175^\circ\text{C}$
- $\Delta T \approx 170^\circ\text{C}$



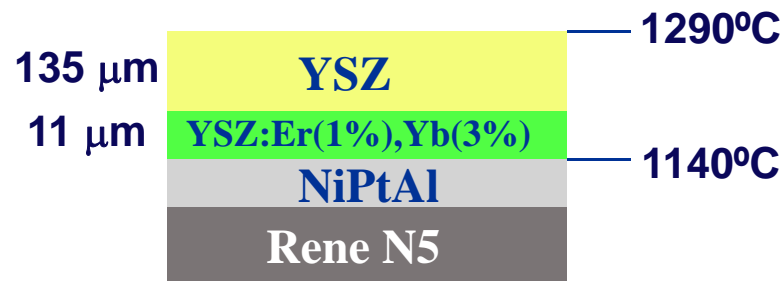
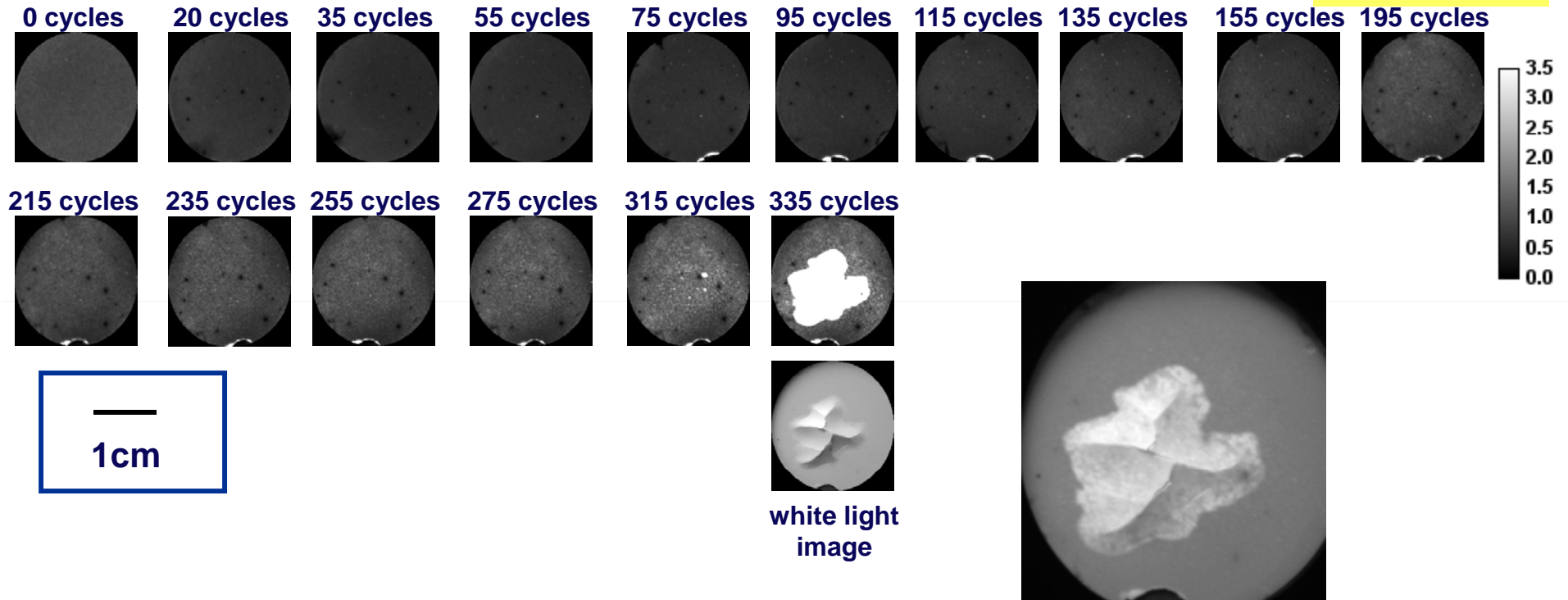
1 cycle = 60 min laser on + 3 min laser off

Upconversion Luminescence Images During Interrupted Laser Cycling

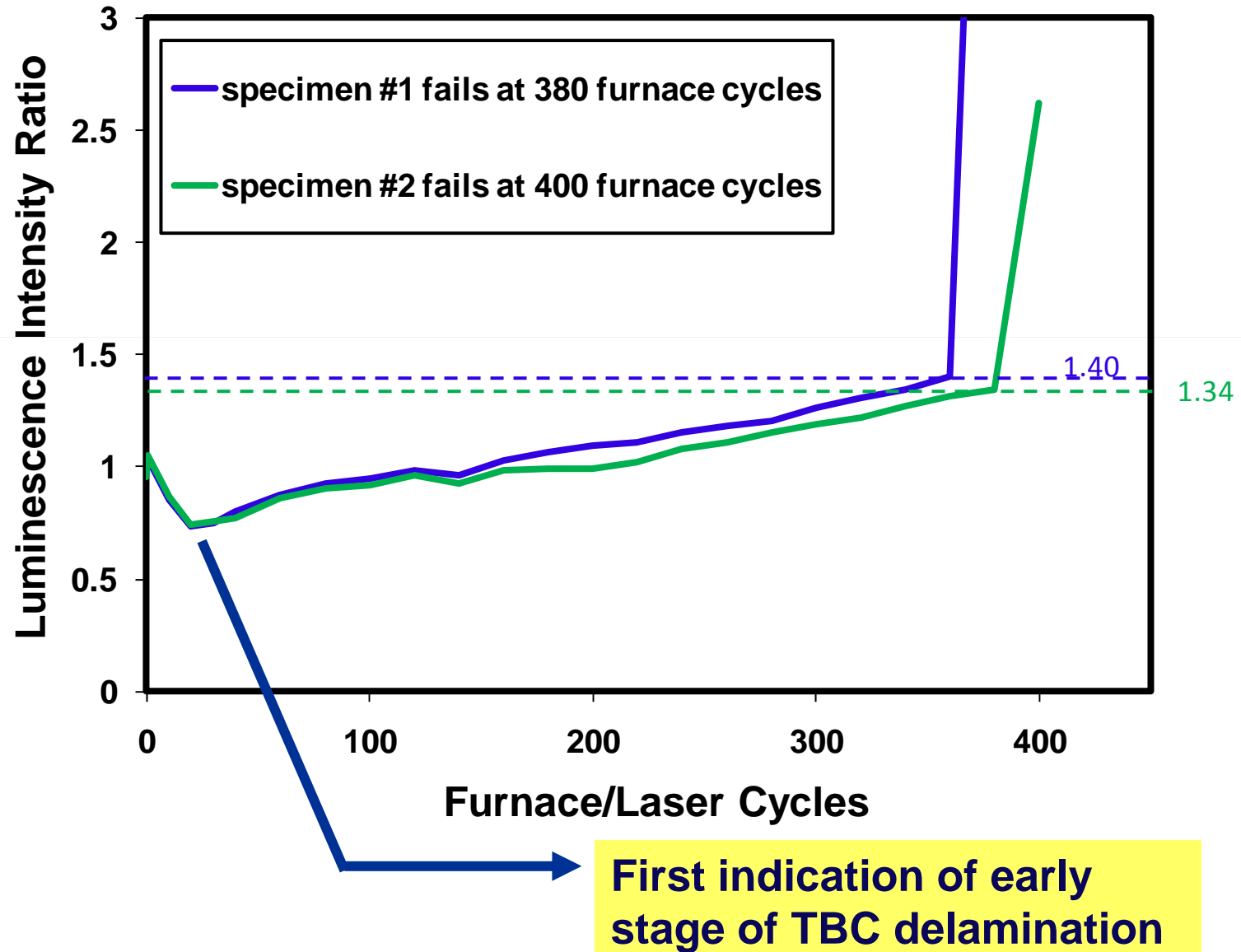
Heat Flux Test #1, $q = 95 \text{ W/cm}^2$

1 laser furnace cycle = 60 min laser on + 3 min laser off

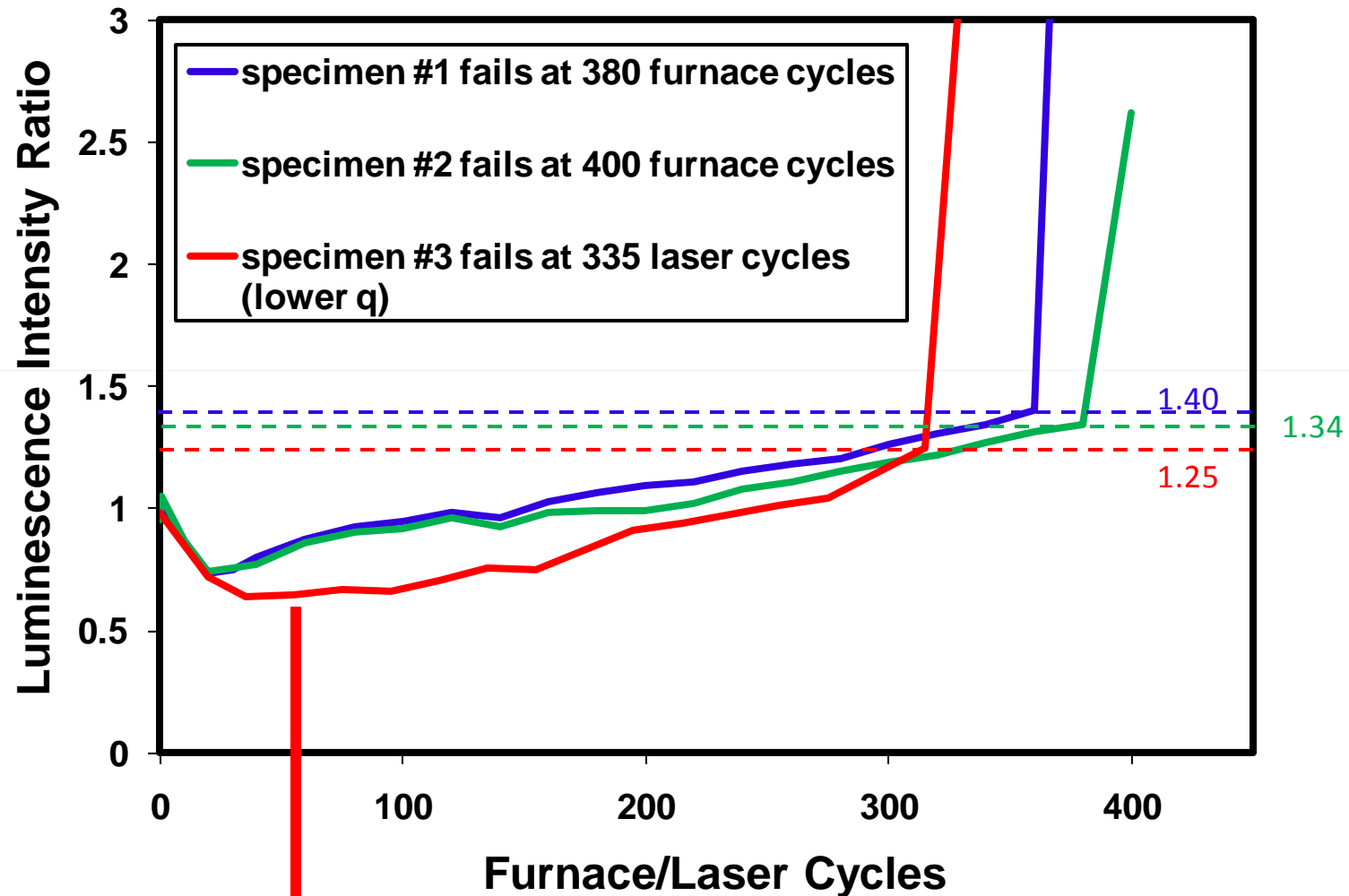
3.25 sec
acquisition



Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling



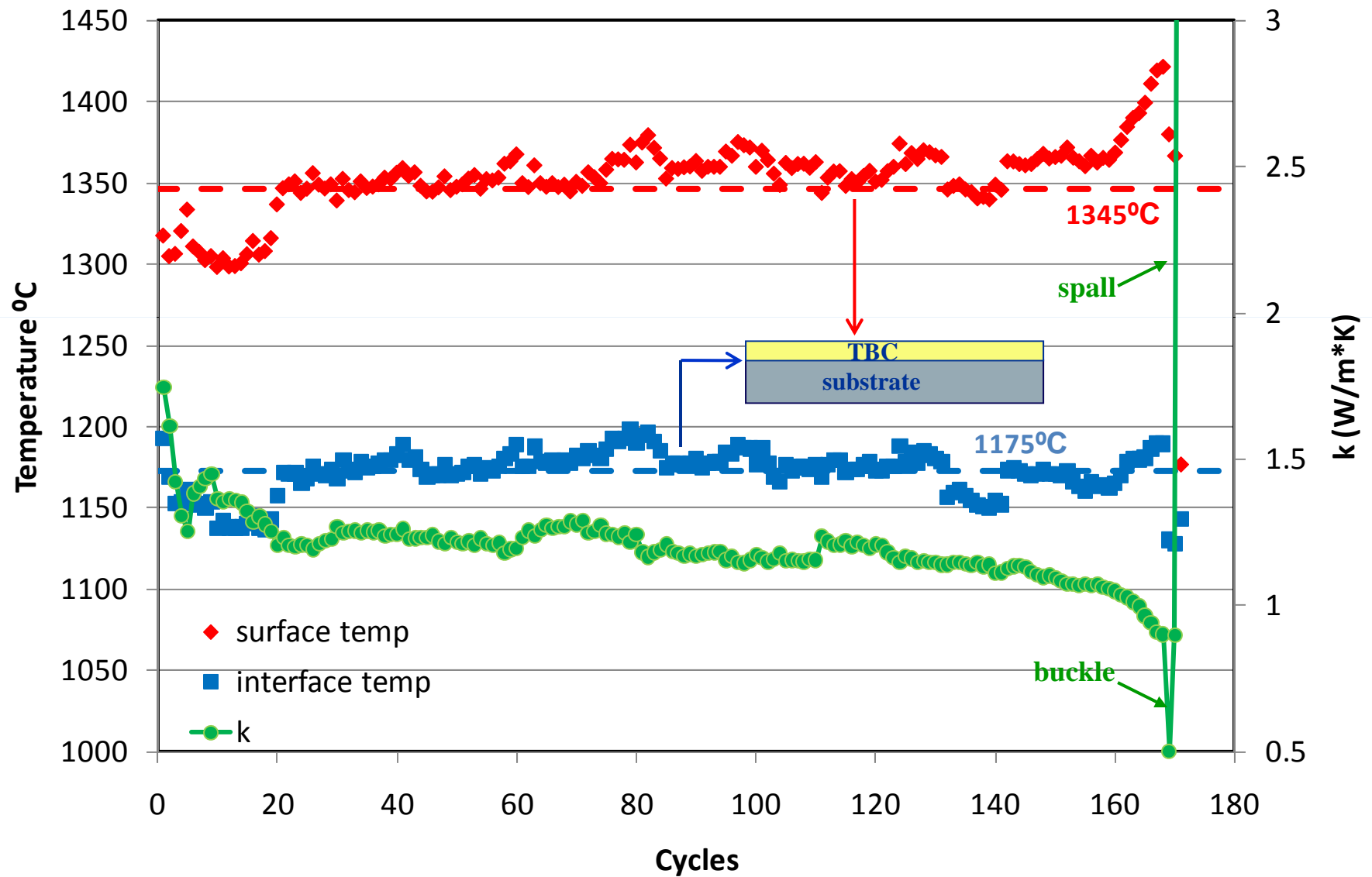
Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling



Laser cycling exhibits an initial incubation stage followed by accelerated delamination progression.

Temperature Sequence During High-Heat Flux Laser Testing

$$q_{\text{thru}} = 125 \text{ W/cm}^2$$

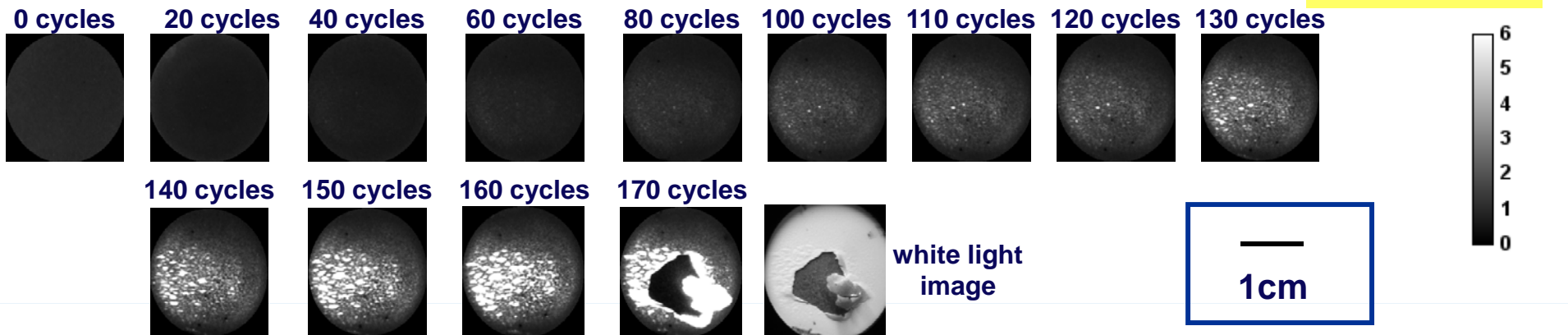


Upconversion Luminescence Images During Interrupted Laser Cycling

Heat Flux Test #2, $q = 125 \text{ W/cm}^2$

1 laser furnace cycle = 60 min laser on + 3 min laser off

3.25 sec
acquisition



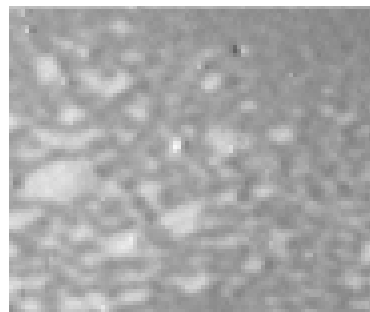
Localized Sub-millimeter Delamination Observed

glancing white
light image

upconversion
luminescence
image

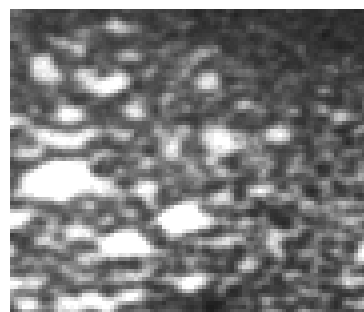
TBC surface
undulations*

Not observed
for furnace
cycled or lower
heat flux test!



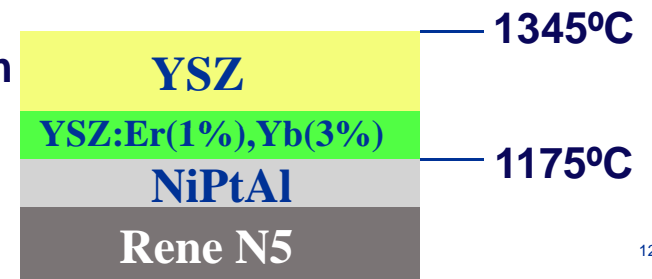
overlay

150 cycles



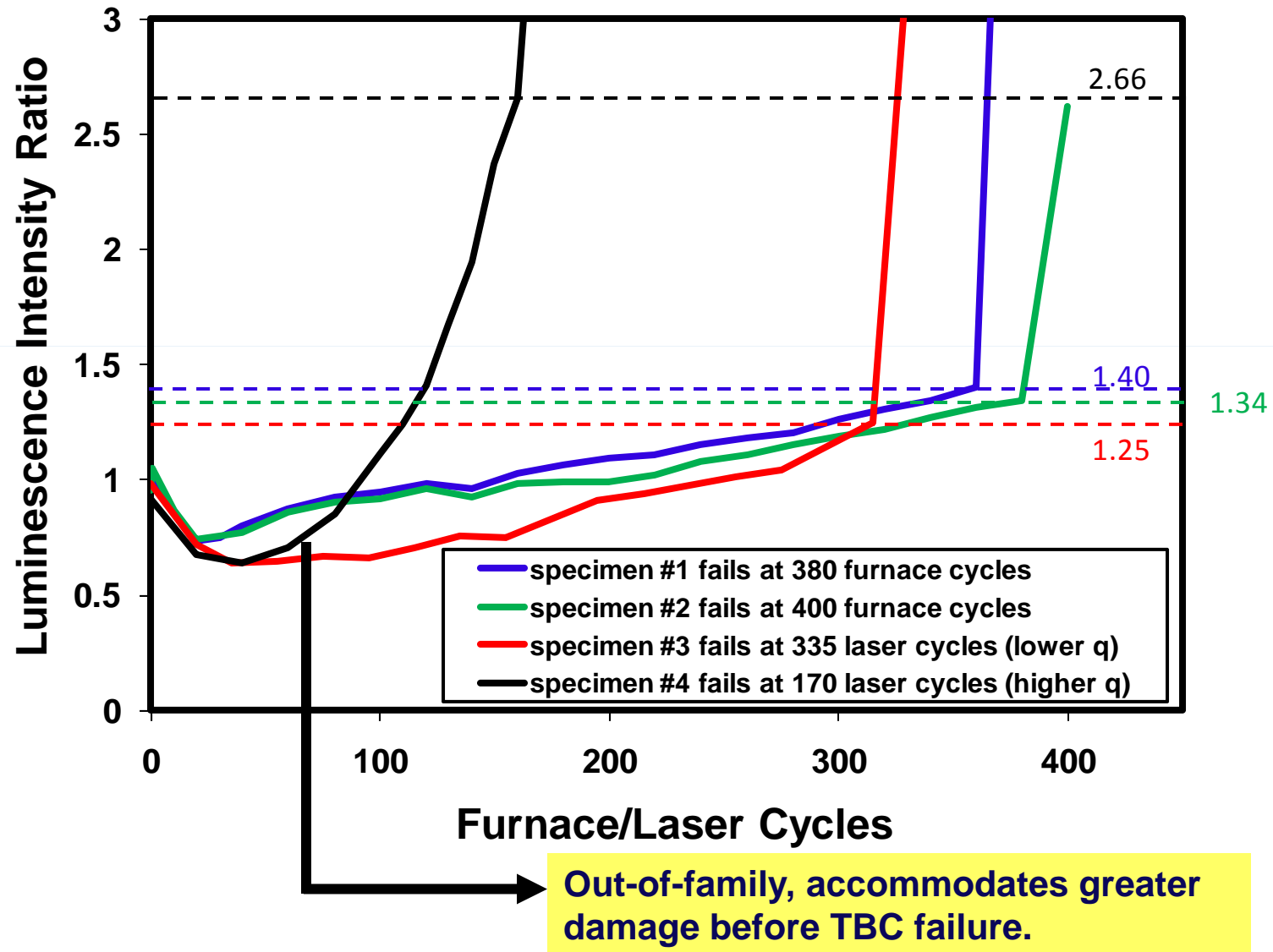
135 μm

11 μm

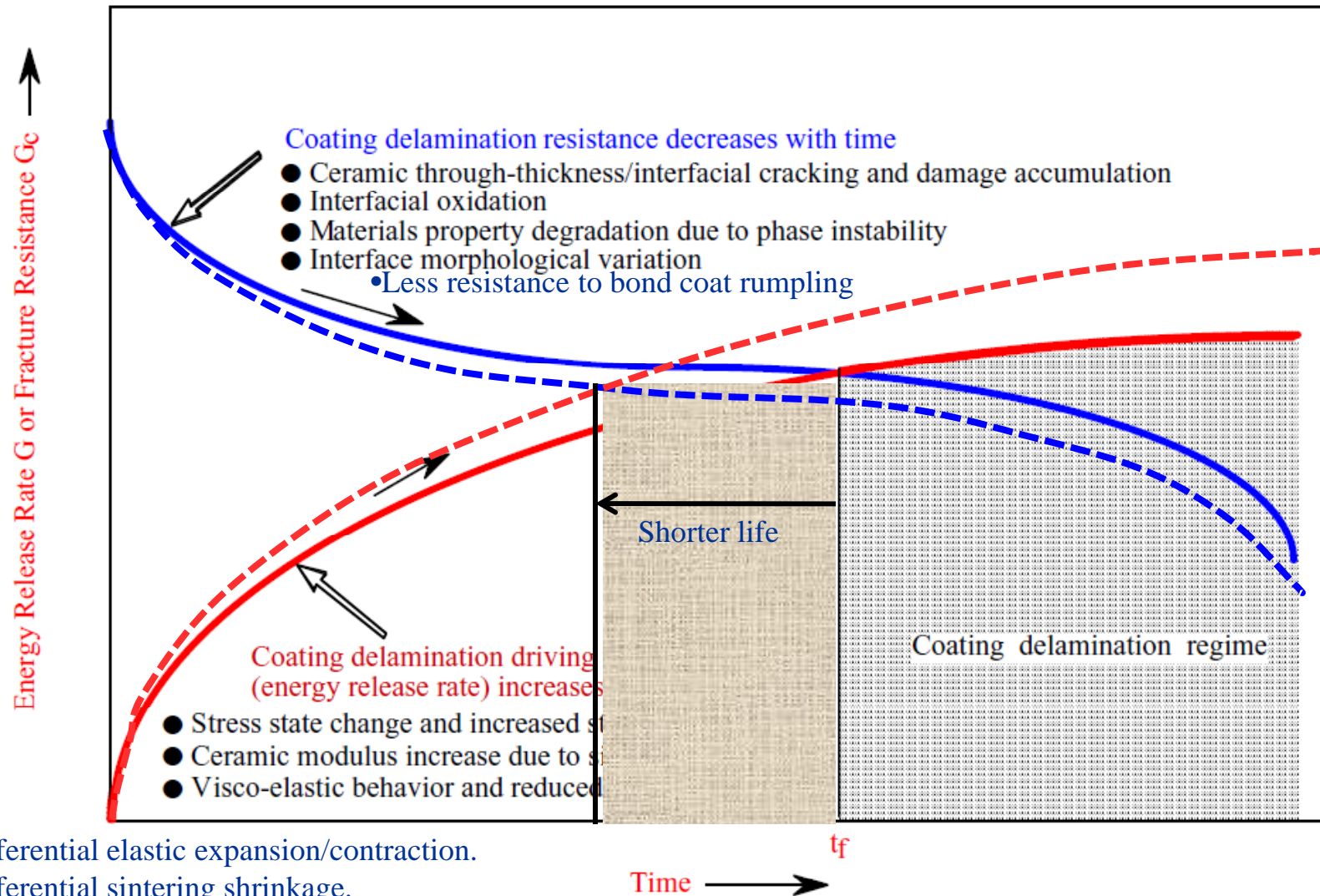


*Tolpygo & Clarke

Comparison of Upconversion Luminescence Intensity During Interrupted Furnace vs. Laser Cycling

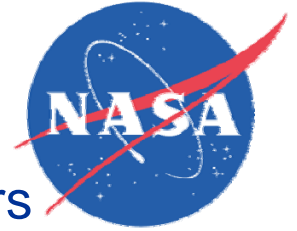


TBC Failure Occurs When Delamination Driving Force Exceeds Delamination Resistance



- Differential elastic expansion/contraction.
- Differential sintering shrinkage.
- Large transient thermal stresses at start of heating/cooling.
- Interface temperature increases as TBC thermal conductivity decreases.
- ΔT across crack produces energy release.

Summary



- Upconversion luminescence imaging successfully monitors delamination progression for TBCs exposed to high heat flux conditions.
- High-heat-flux conditions produce TBC debond progression that accelerates (relative to isothermal conditions).
- High-heat-flux conditions change path of TBC debond propagation (allowing bond coat rumpling).
- Diagnostic life prediction based on damage evolution occurring during isothermal exposures will grossly overestimate TBC remaining life under high heat flux conditions (even with same starting interface temperature).

Acknowledgments

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